# Automated Construction of a Martian Base

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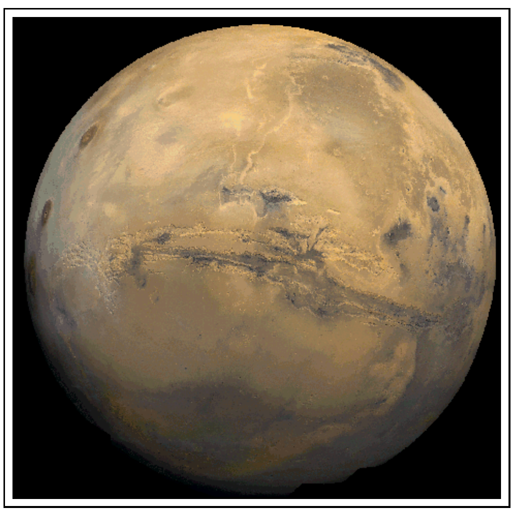
## 1 Introduction



This document describes the construction of a Martian base that will support human exploration. The base will be constructed without a human presence in order to minimize the risk to the crew. The base will be verified remotely before the crew leaves Earth to ensure that all systems are performing as expected.

Life support is the most obvious function the base will have to perform. The crew will require consumables such as food and water. They must also be provided with a controlled atmosphere. The base will use in-situ resource generation (ISRG) as the primary means to provide these services. The ISRG system will extract chemicals from the Martian atmosphere and convert them to usable resources.

Power is a key resource for the base. The primary power needs will be met by an SP-100 nuclear reactor and three Stirling engines. This primary power source can provide 375 kW of power under nominal conditions, which is sufficient to support all base operations. Backup systems are present that can sustain critical functions such as life support and communications in the case of primary system failure.

The base will provide a substantial communications infrastructure. Both Earth to Mars and surface communications are supported. A satellite constellation will be used to provide this capability. Backup systems are also provided that can be used in the event of primary system failure.

Surface operations and science capability is an important aspect of the base design. The base includes two primary laboratories. One laboratory is contained in a lab module that is stationary, and the other is part of a pressurized rover. This mobile science unit (MSU) gives the exploration team the capability of collecting samples and exploring geologic features up to 500 km away. The MSU can operate autonomously from the base for periods up to two weeks with a crew, or it can function robotically for longer periods of time.

A transportation and delivery scheme has also been developed. This scheme requires 4 cargo and assembly missions. The cargo modules will transfer from Earth to Mars on a low energy, near-Hohmann trajectory and then aerocapture into Martian orbit. The cargo modules will then descend to the Martian surface and land within 1km of the chosen landing site. Each cargo module can land up to 15 metric tons on the surface.

Construction will begin as soon as the cargo modules land. The first launch opportunity will send the power and resource generation systems for the base as well as the surface communications infrastructure and two unpressurized rovers in a single launch package. Resource generation will begin as soon as possible. The second launch package will contain the water extraction system, an ascent vehicle, and scientific equipment and instruments.

The remainder of the base will be second launch opportunity. The first cargo mission in this opportunity will transport the science and utility modules and a pressurized science rover to the surface. The final launch will contain the habitation module, crew consumables, and a supplemental life support system.

Base assembly is accomplished through component movement and integration. This work is accomplished primarily with the two unpressurized rovers. The assembly procedure is controlled from the surface with the help of artificial intelligence. The final base is comprised of a central hub, three inflatable utility modules, the power system, and the ascent module.

The base is validated using telemetry from each subsystem. The validation must be successfully completed before sending a crew to Mars.

# 2 Systems

Here several options are investigated for the primary base systems. The advantages and disadvantages of each option are carefully analyzed, and initial system selection is made.

## 2.1 Power

Several methods for providing power to the habitat were considered. Photovoltaic arrays were considered first, but were ruled out for several reasons:

- Martian day/night cycle decreases power output
- Intermittent dust storms on the surface decrease sunlight and degrade cell efficiency
- Hydrogen/Oxygen regenerative fuel cell technology for night storage still in development [8]
- Extremely large surface area required to compensate for low sunlight intensity at Mars orbit
- Temperature fluctuations can change the quantum efficiency of the cells

Wind power was also considered. Windmill systems are not a feasible option for supplying power to the base because the Martian atmosphere is too thin. Batteries and fuel cells were investigated as well. A great deal of heritage surrounding the use of batteries in spacecraft exists, but the long duration of this mission's surface stay makes batteries an inadequate option for power.

The most viable method for delivering power to the base is via a nuclear plant. There has been a significant amount of research into surface nuclear power to support Lunar and Martian bases [8, 7, 5]. We recommend the deployment of a nuclear reactor system to provide the base with power.

## 2.2 Surface Operations

An anticipated surface stay of over 600 days causes surface operations to be particularly important. The crew must be provided adequate tools for scientific exploration and investigation. The crew will be conducting science in both the immediate base vicinity and in remote locations in order to maximize the scientific achievements of the mission.

### 2.2.1 Science

The promise of increased scientific knowledge is a major motivating factor for the human exploration of Mars. Science is thus an important aspect of crew surface operations that must be adequately supported. Our design will include the power and laboratory infrastructure necessary to provide scientific capabilities equal to the International Space Station.

An important part of exploration is geology and sample collection. To facilitate this we will include a mobile laboratory environment capable of conducting scientific studies at remote locations.

The International Space Station allocates approximately 45 kW of electric power to scientific experiments [2]. We will provide the same amount of power to the laboratory module of the base. Unlike the ISS, the base science requirements are geared more towards exploration and sample collection. A considerable amount of hardware to support exploration (microscopes, instruments, sample storage, etc ... ) will also be made available. We will also provide a greenhouse environment for agricultural experiments.

### 2.2.2 Mobility

The extended surface stay for the crew makes surface mobility a necessity. Mars contains many geological features, and access to geological sites of interest is predicated upon the ability to traverse the terrain. Vehicle range is obviously a key consideration in selecting a device for surface operations. A number of vehicle types were considered.

**Ballistic Vehicles**
Robert Zubrin of Martin Marietta Astronautics has conducted an investigation of ballistic vehicles for surface mobility. These "ballistic hoppers" have the capability of bypassing particularly rough terrain to access geologic sites that are inaccessible to surface rovers. This advantage, however is offset by the fact that ballistic vehicles are generally less safe, require more fuel, and are heavier than surface rovers.


**Surface Rovers**
The most likely candidate for mobility on Mars is a surface rover. The Apollo Lunar rover was used in the 1970s and proved the usefulness of surface vehicles in the geologic exploration of planetary bodies. The Lunar rover had a one-way range of 20 kilometers [11]. It is obvious that a vehicle with substantially longer range will be required to conduct a thorough geologic survey of the area surrounding the landing site. We will employ surface rovers for mobility.

We have decided not to use the system described in the MSTS document [1] because of the difficulty associated with constructing the vehicle. Additionally, this vehicle is in an early design stage and at this point would remain an enabling technology for the mission. We therefore conclude that the assumptions governing the MSTS and the goals of our project are mutually exclusive.

### 2.2.3 Intra–Base Mobility

The main base is comprised of a number of pressurized modules. It is crucial to give the crew members the ability to move between modules to perform scientific or maintenance tasks, access sleeping quarters, transfer equipment between modules, utilize communications system, and retrieve dry goods from stowage.

A number of methods to facilitate mobility between modules were considered. These include suited EVA, pressurized "Tram" cablecar that moves between airlocks, and pressurized tunnels for IVA.

The concept of a "shirtsleeve" working environment dates back to the origins of the manned space program. The convenience and ease of working in a pressurized environment without the cumbersome bulk of a spacesuit increases productivity for crew members. The first method for moving between modules, suited EVAs, was ruled out for this reason. The considerable costs and time associated with suiting up to move between modules makes EVAs a poor option. EVAs are best left for sample collection and remote exploration.

The second consideration, a pressurized cablecar that could cycle between module airlocks was also ruled out, for a number of reasons ranging from weight to the precise module orientation required.

The third consideration, a pressurized tunnel system, was decided upon. The Pressurized Mobility Tunnels (PMT) will be constructed of the same material as the TransHab. These flexible tunnels allow the modules to be misaligned and still connected. Crew members are free to move between modules without suiting up or going through lengthy pressurization and airlock interface procedures. The important tasks listed above that rely on ease of mobility are all easily accomplished via PMT. The PMTs will also house interfaces that permit power, communications, air, and water transfer between the modules.

## 2.3 In–Situ Resource Generation

The In–Situ Resource Generator (ISRG) is a device that will utilize elements of the Martian atmosphere to produce consumables for surface operations. The enormous cost per kilogram of payload to transport from Earth to Mars makes surface manufacturing an extremely attractive option.

### 2.3.1 System Types

Many experiments with In-Situ Resource Utilization (ISRU) have been conducted over the years, and the processes involved have become more efficient with each generation. Three ISRG systems were considered, each utilizing a different chemical process. All three processes extract carbon dioxide from the Martian atmosphere and process it to form other, usable chemicals.

**Zirconia/Electrolysis**
The zirconia electrolysis process [12] was conceived of by Dr. Robert Ash of JPL in the 1970s [12]. Carbon dioxide gas is heated to 1000°C, causing dissociation into CO and $O_2$. The gas is piped through porous zirconia tubes, and an electrochemical voltage potential facilitates the collection of $O_2$ molecules. Waste gas consists of $CO_2$ and CO molecules. It has been proposed that the CO be collected and used to manufacture $CO/O_2$ propellant, but the technical difficulties associated with development of engines compatible with a $CO/O_2$ bipropellant have relegated this idea to Mars ascent vehicles [12]. There are a number of disadvantages to a zirconia electrolysis system. A large quantity of zirconia tubes is required to produce enough $O_2$ to support a manned mission, and there is a significant power requirement to support these systems.

**Sabatier-Electrolysis (SE)**
The SE system is based largely on gaslight-era chemical engineering. Components for SE systems have been manufactured for the ISS [12]. SE systems are based on a carbon dioxide/hydrogen reaction which produces methane and water. The water can be electrolyzed to produce $O_2$ and recover half of the hydrogen molecules utilized in the initial reaction. Sabatier reactors developed by Lockheed-Martin have proven 96% reaction efficient, a marked improvement over zirconia electrolysis systems. The system is more robust and energy efficient than ZE systems, but it requires hydrogen to facilitate production. This hydrogen must either be imported from Earth or extracted from the Martian atmosphere.

**Reverse Water Gas Shift (RWGS)**
The RWGS reaction involves reacting hydrogen with carbon dioxide, resulting in carbon monoxide and water. Water electrolysis reaction allows recovery of all hydrogen, making a RWGS reactor an "infinite leverage oxygen machine [12]." The chief power requirement for an RWGS system is in the water electrolysis step (57 kcal/mole compared to 9 kcal/mole for the RWGS reaction).

### 2.3.2 Recommended ISRG System

We recommend the deployment of an SE-RWGS system. Dr. Robert Zubrin has experimented with a combination of an SE and RWGS system such that the heat generated by the SE reactor can be used to provide the heat required by the RWGS reactor [12]. A combined system can thus be modeled by the following reaction [12]:

$$3CO_2 + 6H_2 = CH_4 + 4H_2O + 2CO \qquad (1)$$

and water electrolysis is as follows [12]:

$$2H_2O = 2H_2 + O_2 \qquad (2)$$

The result is a system that creates 4 kg of methane and 16 kg of oxygen for each 1 kg of hydrogen provided to the system.

## 2.4 Life Support

One of the major obstacles to human exploration of the universe is our dependence on a rigid set of environmental conditions. Humans need food to eat, water to drink, oxygen to breathe, and an atmosphere within strict tolerances of temperature, pressure, and gas concentrations to live in. Our species is fragile, and in order to survive in space we must take our atmosphere with us wherever we go. The function of an Environmental Control and Life Support System (ECLSS) is to provide these basic human needs in inhospitable environments, such as in space or on the surface of Mars.

### 2.4.1 Functions of the ECLSS

The ECLSS must perform several critical functions including:

- Atmosphere revitalization
- Atmosphere control and supply
- Temperature and humidity control
- Water recovery and management
- Food supply, storage, and preparation
- Waste management
- Radiation protection

These functions must be performed for a crew of five continuously and reliably for up to a 650-day mission on the Martian surface.

The ECLSS is critical to the success of the mission and the safety of the astronauts. With this in mind, the ECLSS for this base design will strive to have several levels of functional and design redundancy in order to ensure crew safety.

### 2.4.2 ECLSS Types

There are three general types of life support systems that can be used for a Martian base: open loop, physical/chemical, and bioregenerative. These general types of systems will now be defined, and the advantages and disadvantages of each will be discussed.

**Open Loop Systems**

Open loop life support systems operate by replacing consumables on a regular basis from the Earth. This type of system is the easiest to implement, as supplies are constantly replenished and used materials are simply discarded from the base. This is a feasible option for a single, short-duration mission; however, in order to sustain a prolonged presence on the Martian surface this option becomes far too costly to implement as the primary base life support system.

**Physical/Chemical Systems**

Physical/chemical systems operate using a combination of physical and chemical processes to recycle resources brought from the Earth. These types of systems are currently employed on the Space Shuttle and International Space Station. An example of this type of system is the Lithium Hydroxide canisters used to scrub the air of $CO_2$ during Shuttle missions.

The disadvantage in using a physical/chemical system, however, is that it cannot be one-hundred percent efficient. This lack of total efficiency results in consumable losses that have to be replaced in some manner; either from stored reserves or in-situ resource utilization. In addition, many physical/chemical systems are not recyclable. Once these systems reach their design limit they must be discarded and replaced with new systems that must be transported from Earth. The water vaporation and recovery process (WAVAR, shown schematically in Figure 1) is one such physical/chemical system that we will use to extract water from the Martian atmosphere.

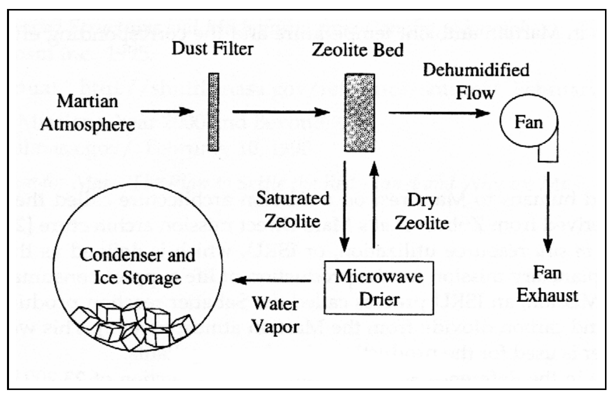



Figure 1: Schematic WAVAR Process [4]

**Bioregenerative Systems**

Bioregenerative systems are systems that use only biological elements (such as higher plant life) to regenerate organic products. This type of system "takes care of itself," and an example of one is the Earth itself. The development of this type of system is absolutely necessary for a continued human presence on Mars.

### 2.4.3 Recommended ECLSS

For the base, a combination of all three types of life support systems will be utilized. In this manner, multiple levels of redundancy can be built into the system to provide an adequate measure of safety for the crew.

## 2.5 Communications

Hardware on the surface of Mars is useless without reliable communications back to Earth. A Martian communication network must address Earth-Mars and Mars-Mars transmission. The exploration of Mars will greatly stretch the current space communication network. For example, the Mars Pathfinder mission returned 30 Megabits per day (Mb/sol). The time averaged bandwidth for the Mars-to-Earth link was 300 bits per second (bps) [3]. A communications link to support a permanent base on Mars must provide much more bandwidth. There are two basic networking methodologies that can used to create a Mars Network: peer-to-peer networking and a central-relay (or hub) network.

### 2.5.1 Peer-to-Peer Networking

A peer-to-peer network uses direct links between all the deployed assets and Earth. This method has been used for the majority of the NASA interplanetary mission. These missions included Mariner, Viking, and Pathfinder.

These types of systems have the benefit of being stand-alone and based on heritage technology. However, this means each asset must have the weight, complexity, and power penalties associated with a Mars-Earth link. A typical link will require:

- A directional antenna
- Steering mechanism
- Power amplifier
- Heat-removal device
- Large solar panels
- Battery capacity
- Power handling electronics

In the Mars Pathfinder and the Mars Surveyor '98, the mass of the link hardware outweighed the science payload [10].

### 2.5.2 Central Relay Networking

A more modern approach is the relay station/satellite. This method requires a single Mars-to-Earth direct link coupled with low power UHF (ultra-high frequency) communications for the Mars system. The relay station may be a single satellite, a satellite constellation, a high power ground based system, or some combination. The ground station is the most limited option (because it decreases the amount of time the base could be in contact with the Earth), and would likely only be used as a secondary system for a manned base on Mars. Whatever system is used must provide high-bandwidth, reliability, and expandibility.

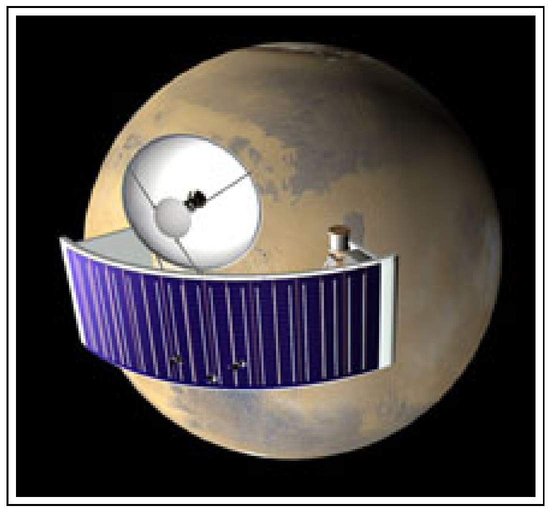


Figure 2: A MicroSat Design Configuration [9]

Relay satellites (a possible configuration shown in Figure 2) allow the science rovers to be lighter and use less power. The satellites will increase data return and allow improved surface navigation/landing. There are a multitude of design options for a communications satellite constellation. These constellations range from the low cost single craft [10] to larger constellations consisting of low orbit microsats coupled with larger aerostationary satellites [9]. Aerostationary satellites are in similar orbits to Earth geostationary communication satellites; that is, they stay above the same spot on the Mars surface. The Mars Network system currently under design by JPL is a central relay network that provides high bandwidth data return, reliable coverage with multiple satellites, and plans for expandibility [9].

# 3 Base Design

The initial Mars outpost will consist of six modules. The three living and working modules will be based on the current TransHab being developed at NASA Johnson Space Center [6]. The fourth module will be the ascent stage coupled with the resource generation systems. The final module will be the nuclear based power plant. The three living/working space modules will be design for critical failure redundancy. The hub of the base contains the primary base infrastructure components. These components include:

- ISRG
- Docking Adapters
- Communications Array
- Power Distribution System
- Airlock

A schematic design for the base is shown in Figure 3.

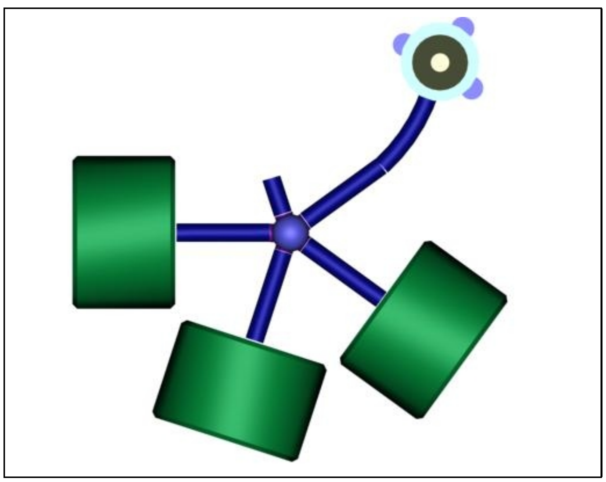


Figure 3: Schematic Base Design

## 3.1 Passageways

The astronauts will move between modules through inflatable tunnels made of the same material as the TransHab. The heating and air circulation for each hall will be provided from the modules connected to the hall. The tunnels will be flexible and extendable. This will allow small shifts in the location of each module without stressing the interconnecting passages. The flexibility will facilitate the construction of the base.

Without flexible interconnections all of the modules would have to aligned accurately in all six degrees of freedom and moved into place. Current estimate for the TransHab indicate a mass of 13 metric tons [6]. The alignment of two or more ten-ton objects would require an unnecessarily heavy infrastructure for the construction. The weight of the construction equipment can be better used for scientific or life support equipment.

## 3.2 Docking Interface

Each habitat module on Mars will be equipped will standard connector interfaces. The interfaces will permit the redundant transfer of power, communications network, air, and water throughout the base. The connections will also provide hallways between modules for the crew members. The connectors will be available on each end of all the modules. The connectors will come in male and female flavors.

The docking interface will act as a multi-use extension cord to connect the living/working modules. The use of these connectors will allow the flexibility in the assembly of the base. The docking interface will provide 15 meters of linkage between two modules.

### 3.2.1 Power Connection Requirements

The power conduit will have two separate connections. Each connection will be able to handle two-thirds of the base power requirements. All fully operational interfaces will pass 133% of the base power to the downstream modules. All power connections will be equipped with resetable circuit breakers. This will protect one module from being influenced by a power overload or short circuit in other portions of the base.

### 3.2.2 Communications Network Requirements

The base will be equipped with a network for computer communications through out the base. This methodology should leverage the large commercial sector involved involved in computer networking. The interface will have two fully redundant connections. The physical wiring should allow for computer connections as well as for stand-alone sensors based in and around the base. The network systems should be sized for the future growth of the station.

### 3.2.3 Water Transfer

The plumbing of the station will be very important. Water will be needed throughout the station. Clean potable water will be needed in the galley and living quarters. Water is also used in lab environments and other work areas. Each interface should provide the capacity to deliver 100% of the base daily requirements.

The disposal of water may pose a greater problem. The water must be filtered and recycled. Various levels of contamination will require different filtering methods. Three levels of disposal water will be provided. Each system will be separate and routed to the corresponding to filter/cleaning system. The disposal system must be sized to match the supply system with a safety and growth factor.

### 3.2.4 Air Transfer

The base will require central air recycling and heating for the base. If air circulation and heating ducts are used, they must be routed through the connectors. The air ducts will require a significant amount of volume and must be sized for the heating of the base. For the detailed design of the base heating and cooling systems it be easier and more efficient to circulate the air through the human passages themselves rather than through separate ducts.

### 3.2.5 Physical Connection

The connection system between the modules must provide an airtight seal and a strong connection. The connection of two modules must be accomplished without astronaut EVA intervention. The system must be made of materials that are inert in the Martian environment. The thermal expansion of all the materials must be closely matched because of the large temperature gradients the structure will face on the Mars surface.

The docking interface will have an independent backup system. Airlocks will be provided at each end of each module to allow suited crew member ingress and egress. These airlocks can be sealed to isolate any leaks that may develop in the seal or the hallway material. Multiple airlocks also increase base modularity.

The initial physical contact will be achieved via the use of cables that move from the male connector to the female connector. These guide cables provide alignment, strength for the passageway, and are used as a method for moving the docking systems together.

Once the two faces are touching electromagnetic latches will be closed to hold the joint together.

## 3.3 Construction Rover

The construction rover is based on the technology pioneered by JPL missions to explore Mars and the rover technology used to explore the oceans of the world. Current technology allows unmanned rovers to lay telecommunications cable, retrieve artifacts, inspect oil rigs, and more. This work is all done in the harsh environment of the ocean floor. The Martian environment poses similar obstacles to robotics.

The construction rover will have wheels for mobility. The system will be powered by batteries and will have the ability to recharge from the base power grid. The major component of the rover is the robotic arm. The arm can be a miniature version of the shuttle or space station arm. A manipulator hand is very important to pickup parts, place things, and flip switches.

One of the major limiting factors in current robotics is the controlling artificial intelligence. The majority of the working robots are tele-operated. This method of control is not feasible for Mars because of the time lag in communications. The Martian rover must be able to complete tasks without human intervention. However, the rover needs to be relatively lightweight and robust enough inspect a nuclear system. Therefore, the rover will contain sensors including stereo vision and lights, but the intelligence of the system will be contained in the base computers. In this way, the rover will be tele-operated by a computer program running on the base system. This setup will provide more processing power and storage than otherwise available on a rover. The system should have the ability to act in wireless mode (through an UHF radio link) or with an umbilical cord to provide power and control inputs.

# 4 Base Construction

The robotic assembly of the outpost on Mars requires a complicated set of steps to provide the functionality for human habitation.

The general construction sequence includes:

1. Land initial units on Mars

2. Move to assembly area

3. Align first two units within 15 meters
4. Begin docking procedure
5. Once docking procedure has be completed the modules are connected
6. Base validation begins

This procedure will be repeated for each new elements added to the outpost. Certain cargo missions use a different assembly procedure, however, that will be described later.

## 4.1 Launch Manifest

The orbits of Earth and Mars result in a 15 year trajectory cycle which is divided into 7 launch windows. This configuration results in a launch opportunity about every 26 months. The Reference Mission begins with the first launch of a Mars cargo transport in the year 2007, and this mission will begin with the same initial launch opportunity. For each of the launch windows, it is assumed that 2 successful launches will be made (for a total of 4 launch packages delivered to the Martian surface). This split launch approach will allow base components to be validated before additional pieces are sent. The following launch manifest assumes the capability to lift 15 metric tons to the surface of Mars. This more feasible than the reference mission assumption of 50 metric tons deliverable to the surface [7].

## 4.2 Base Deployment

The base will be composed of the modules mentioned previously and a number of subsystems. All systems must be deployed and integrated before the base will be fully functional.

Table 1: First Launch, September 2007

| System | Mass (tons) |
|---|---|
| Power System (NPU, PDS) | 8.7 |
| Resource Generator (ISRG) | 1.0 |
| S-Band Communication System | 1.0 |
| Construction Rover | 0.5 |
| Utility Rover (UPR) | 2.0 |
| Seed Hydrogen | 1.5 |
| Total Launch Weight | 14.7 |

Table 2: Second Launch, September 2007

| System | Mass (tons) |
|---|---|
| Water Extraction (WAVAR) | 5.0 |
| Ascent Module (MAM) | 5.4 |
| Scientific Equipment (terrain mapping, soil sample collection and analysis, etc.) | up to 4.6 |
| Total Launch Weight | 10.4-15 |

### 4.2.1 NPU Deployment

The NPU is the primary power source for the base. Radiation considerations dictate that the reactor be placed 2.5 km from the main base. The reactor will be separated from the NPU deployment cart. The NPU deployment cart contains wheels, a spool with 2.5 km of power cable, and the Power Distribution System (PDS). The PDS is the "wall outlet" that the main base draws power from. The deployment cart also houses the ISRG and an s-band communications antenna and will be the eventual "hub" of the main

Table 3: Third Launch, October 2009

| System | Mass (tons) |
|---|---|
| Science Module (SM) | 7.5 |
| Utility Module (UM) | 6.5 |
| Science Rover (MSU) | 0.885 |
| Total Launch Weight | 14.885 |

Table 4: Fourth Launch, October 2009

| System | Mass (tons) |
|---|---|
| Habitation Module (HM) | 5.5 |
| Food Cache | 2.2 |
| Experimental ECLSS (life support) | up to 7.3 |
| Total Launch Weight | 7.3-15 |

base. The UPR will tow the NPU's deployment cart 2.5 km and set down the PDS and ISRG on the site selected for the main base.

#### 4.2.2 ISRG Deployment

The ISRG, which arrives in the first launch package with the NPU, is situated below the PDS. It will already be connected to the PDS and will begin receiving power when the NPU powers up. The ISRG requires no external assistance to begin manufacturing oxygen and bipropellant. One metric ton of seed hydrogen will be included in the first launch package for use the surface. The ISRG will immediately begin to process the seed hydrogen and will exhaust its stores, creating 12 metric tons of bipropellant and 8 metric tons of excess oxygen. The bipropellant will be used to fuel the UPR which will in turn be used to tow the ISRG/PDS "hub" to the site selected for the main base.

#### 4.2.3 Rover Deployment

Three rovers are included in the mission scenario. They arrive on the surface unpowered and unfueled. The UPR and construction rover are included in the first launch package. When the NPU powers up, the ISRG utilizes seed hydrogen and creates bipropellant for the UPR. The UPR then moves the ISRG/PDS hub away from the reactor towards the main base site. The construction rover is a battery-operated rover that remains close to the central hub and is capable of using the PDS to recharge its power supply. The MSU arrives in the third launch package. The UPR will retrieve it and tow it to the ISRG for fueling and power.

#### 4.2.4 WAVAR Deployment

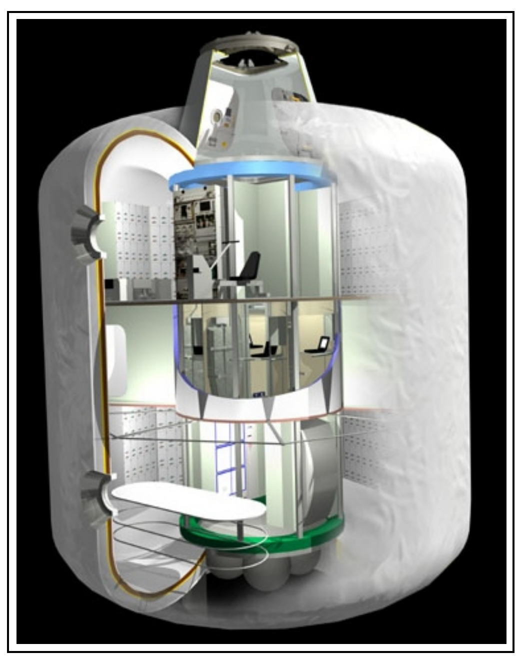
WAVAR arrives in the second launch package. It requires power from the PDS to operate. The UPR will go to the second launch landing site, retrieve the WAVAR, and transport it to the central hub. Once receiving power from the PDS, WAVAR will provide water for the crew and seed hydrogen for the ISRG.

#### 4.2.5 Mars Ascent Module Deployment

The Mars ascent module (MAM) arrives in the same launch package as the WAVAR. The 5.5 metric ton [7] vehicle will be moved by the UPR to the main base site. A PMT will link the MAM to the central hub. This will allow the crew to access the MAM without EVA. This is an obvious advantage over mission scenarios that require crew members to suit up in order to access an ascent vehicle. The time required to prepare all crew members for EVA can be crucial to survivability in an emergency, and the ability to quickly ingress the MAM in a crisis could save lives.

#### 4.2.6 TransHab Deployment

The majority of habitable crew space is comprised of three TransHab modules (the SM, HM, and UM). These are scaled-down versions of the element envisioned for deployment on ISS. Each module serves a different purpose, but all three are deployed in an identical manner.



**Preliminary Movement/Orientation**
Regardless of the launch package or module purpose, each module will be moved from its landing site to an area near the main base by the UPR. Each module contains a 15 meter section of PMT on one end. It will also be necessary for the UPR to orient the module such that the end containing the section of PMT is oriented toward its designated docking ring on the hub. The UPR must therefore move the module to within 15 meters of the base and orient the PMT ring to mate with the hub. The PMTs are flexible enough to mate module to hub even though the two are misaligned or off axis. It should be obvious that a module positioned closer to the hub will have more PMT available to take up any misalignment.

**Guide Cable Connection**
After the UPR aligns the module with its mating adapter on the hub, the construction rover will connect three guide cables from the module to the hub. The cables will be contained in the PMT of the module. The cable holder and the corresponding catch will be painted to allow easy identification by the rover vision system. After all three cables are secure, the PMT will be ready to dock the hub.

**PMT Extension and Docking**
Once the module is physically connected to the hub by guide cables, the docking plate from the module is pulled into place by wheel bogeys housed in the PMT. The rover can provide video of the connection or in case of motor failure, it could extend the tunnel by pushing the docking plates together. The hub contains a winch that can be used to pull the PMT to the docking adaptor in the event of wheel bogey failure. Once the plates are flush, electromagnetic latches will seal the PMT to the hub and allow the module to be pressurized. The configuration of the docking plates is polarized and machined so that the pieces slide together creating the electrical, network, water, and air connections. After the physical connection, the circuit breakers can be thrown to power up the module. After all modules are fully powered, base validation can begin.

# 5 Base Validation

Base validation is a key aspect of the mission that must be satisfactorily completed before any human crew is sent to Mars. Validation will require testing all of the critical functions of the base and ensuring that they work to within given specifications. the validation phase of base construction is greatly facilitated by the extensive telemetry data that will be collected in the base during nominal operations. The key components that must be validated include:

- Power Systems
- Communications
- Life Support Systems
- Science Systems
- Transportation Systems
- Ascent Module

## 5.1 Power Systems

The power system is a key system that all base functions depend upon. The power system is so critical that if it is not functioning properly the validation phase cannot even be initiated.

A key element of the power system validation is that the nuclear reactor is functioning intact and within specifications. It is critically important that the NPU not leak excessive amounts of radiation, as this would endanger the crew. Geiger counters will be used at the base site to measure radiation levels and verify that they are within expected limits. These measurements will also be useful in determining the ambient radiation level due to solar activity. The base will already have been designed to withstand known levels of Martian radiation, but these tests will serve to validate those design limits.

The reactor core temperature must also be monitored to predict meltdown. Fluctuations in reactor core temperature can indicate a heat exchanger malfunction. The offending heat exchanger can be isolated via onboard thermocouples.

Additionally, each of the four Stirling engines will need to be validated. This can be done on an individual basis before the base is operating at its nominal power level. Each engine will be run up to its maximum rated power while its health is monitored. We will look for particular operational anomalies such as severe outlet temperature fluctuations, excessive vibration, inconsistent rotational speed, and inconsistent power output.

A mathematical model of the power system will be created. This model will be run on Earth during the construction and validation phases. Results from the model will be compared to system sensor output as a means to detect differences and failures. The mathematical model can also detect failures in the sensors themselves by detecting results that are not physically possible. Once the base is operational, the model will be run in real time on the base control computer systems.

## 5.2 Communications

The communications system is another system that must be functioning properly when the validation phase of the base construction is begun. This system will be required to send massive amounts of data between Earth and Mars while validating all other systems.

Both the satellite transmitter relay and the base backup system will be verified for data integrity and reliability. This is particularly important for detecting any unanticipated interference that might be present in the base vicinity. Additionally, the communications subsystems on the MSU and UPR must be verified. These systems should be able to talk to each other, the base, the central relay satellite, and (to a very limited extent) to Earth.

## 5.3 Life Support Systems

Validating the life support system will concern the module artificial atmospheres and produced resources. The atmosphere in each module (and the MSU) must be verified as conforming to predetermined specifications. These specifications will prescribe the temperature and partial pressures of gases. The carbon dioxide filtration systems must be verified by introducing $CO_2$ into the closed system and monitoring the atmosphere throughout the filtration process. All of these atmospheric monitoring processes will continue for the lifetime of the base. The validation functions will therefore be an intrinsic part of the base design. Validation simply requires transferring this data to Earth for analysis.

The water and oxygen production functions of the ISRG and WAVAR systems must also be verified. Chemical tests will be performed to guarantee that the purity of these resources are within tolerable limits.

## 5.4 Science Systems

The individual science packages will be validated by their respective Earth-based support teams. The main base computer will run a battery of tests and transmit the results to Earth via the communications infrastructure for debugging purposes.

## 5.5 Transportation Systems

The MSU and UPR will be validated during the construction phase of the base. The UPR will already be validated through the construction procedure since it will be used to position components on the surface. These two devices must be capable of powering up and operating autonomously. The internal combustion engines will be verified by checking for excessive vibration and inconsistent torque output. These devices will be preprogrammed with a set of validation tasks that can be conducted on the surface under the guidance of the base control computers.

The surface rovers depend heavily on the ISRG's ability to produce and transfer fuel. The ISRG must therefore be fully functioning and have stored a sufficient amount of fuel. Again, the base construction is dependent on this functionality, so a successful construction phase will validate the ISRG fuel production capabilities.

## 5.6 Ascent Module

The Ascent Module will be powered up and pressurized before the crew arrives. This will check for leaks and allow engineers on Earth to verify that all its computer systems are functioning properly. It will also be partially fueled to check for leaks in the propulsion system tanks, hoses, valves, etc...

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